Spontaneous subatomic mass-energy interconversion as a physical origin of wave-particle duality

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Abstract

Wave–particle duality is a foundational feature of quantum mechanics, yet the physical processes underlying single-particle interference remain an open question. Here I investigate a dynamical mechanism based on spontaneous stochastic mass–energy interconversion at subatomic scales. By allowing particle mass to fluctuate in time, consistent with Einstein's mass–energy equivalence, I derive a modified Schrödinger equation containing a stochastic kinetic-phase term. Applying this framework to the double-slit experiment, I show that interference arises from coherent, path-dependent phase accumulation while remaining fully compatible with localized detection events described by standard quantum mechanics. The model yields a closed-form expression for fringe visibility, predicts a characteristic momentum- and mass-dependent decoherence rate, admits a path-integral formulation, and enables direct experimental bounds using existing neutron, electron, and atom interferometry data. These results provide a physically motivated, testable mechanism underlying quantum interference without altering the formal axioms of quantum mechanics.

Key words: Wave–particle duality; quantum interference; stochastic quantum dynamics; mass–energy equivalence; fluctuating mass; modified Schrödinger equation; interferometry; fringe visibility; decoherence mechanisms; quantum foundations

1. Introduction

The double-slit experiment remains one of the most profound demonstrations of quantum behavior. Individual particles-electrons, neutrons, atoms, and even large molecules-produce interference patterns when not observed, yet appear as localized detection events upon measurement. While quantum mechanics successfully predicts these outcomes using wavefunctions and the superposition principle, it does not specify a physical mechanism responsible for this dual behavior.

Standard interpretations often treat wave-particle duality as an irreducible feature of nature, invoking complementarity, observer-dependent collapse, or purely epistemic probability amplitudes. However, quantum field theory already accommodates fluctuating energy densities and transient particle creation, suggesting that mass and energy may not be strictly static properties at the most fundamental level [1].

In this work, I investigate whether **spontaneous stochastic mass-energy interconversion** can provide a physical origin for wave-particle duality. Building on a framework in which quantum uncertainty emerges from dynamic mass fluctuations, I apply this idea to the canonical double-slit experiment and demonstrate that interference follows naturally from stochastic kinetic-phase dynamics, without modifying the axioms of quantum mechanics.

2. Results

2.1 Stochastic mass-energy dynamics

I postulate that a particle's inertial mass fluctuates in time according to

$$m(t) = m_0 + \delta m(t),$$

where m_0 is the mean rest mass and $\delta m(t)$ is a stationary stochastic process satisfying

$$\langle \delta m(t) \rangle = 0, \quad \langle \delta m(t)\delta m(t') \rangle = \sigma_m^2 e^{-|t-t'|/\tau_c}.$$

These fluctuations correspond to spontaneous mass-energy interconversion via

$$\delta E(t) = c^2 \delta m(t),$$

and conserve energy in expectation.

Substituting $m(t)$ into the kinetic Hamiltonian yields a time-dependent operator,

$$\hat{H}(t) = \frac{\hat{p}^2}{2m(t)} + V(\mathbf{x}),$$

which, expanded to first order in $\delta m(t)$, becomes

$$\hat{H}(t) \approx \frac{\hat{p}^2}{2m_0} - \frac{\hat{p}^2}{2m_0^2}\,\delta m(t) + V(\mathbf{x}).$$

The Schrödinger equation therefore acquires a stochastic kinetic-phase term,

$$i\hbar \frac{\partial \psi}{\partial t} = \left[\frac{\hat{p}^2}{2m_0} + V(\mathbf{x}) - \frac{\hat{p}^2}{2m_0^2}\,\delta m(t)\right]\psi.$$

Emergence of interference in the double-slit experiment

After passing through the slits, the wavefunction is

$$\psi(\mathbf{x}, t) = \psi_1(\mathbf{x}, t) + \psi_2(\mathbf{x}, t),$$

and the detected intensity on the screen is

$$I(\mathbf{x}) = |\psi_1|^2 + |\psi_2|^2 + 2\Re(\psi_1^* \psi_2).$$

The stochastic kinetic term induces a random phase along each path j,

$$\phi_j(t) = -\frac{1}{\hbar}\int_0^t \frac{p^2}{2m_0^2}\,\delta m_j(t')\,dt'.$$

The interference term therefore depends on the relative phase

$$\Delta\phi = \phi_1 - \phi_2,$$

demonstrating that interference arises from **coherent stochastic phase accumulation** rather than an abstract wave ontology.

2.2 Fringe visibility and experimental signature

Defining the coherence functional

$$\gamma(T) = \langle e^{i\Delta\phi(T)} \rangle,$$

the ensemble-averaged intensity becomes

$$\langle I \rangle = |\psi_1|^2 + |\psi_2|^2 + 2|\psi_1||\psi_2|\,|\gamma(T)|.$$

For Gaussian mass fluctuations with correlation time τ_c, and for flight times $T \gg \tau_c$, the fringe visibility obeys

$$\boxed{\mathcal{V}(T) = \mathcal{V}_0 \exp\left[-\frac{p^4}{4m_0^4\hbar^2}\sigma_m^2\tau_c T\right].}$$

This expression predicts:

- exponential decay of interference visibility with propagation time,
- a strong p^4 momentum dependence,
- reduced decoherence for heavier particles at fixed kinetic energy.

2.3 Which-path detection and decoherence

Which-path measurements couple to the particle's kinetic energy and therefore condition the stochastic mass-energy phase. This destroys phase coherence,

$$|\gamma| \to 0,$$

eliminating interference without invoking observer-dependent collapse. Decoherence emerges dynamically from mass-energy phase conditioning.

2.4 Experimental constraints

Existing interferometry experiments directly constrain the model parameters. From a measured visibility $\mathcal{V}$ over time T,

$$\sigma_m^2\tau_c \leq \frac{4\hbar^2}{p^4}\frac{-\ln(\mathcal{V}/\mathcal{V}_0)}{T}.$$

High-visibility neutron interferometry experiments already impose stringent upper bounds on $\sigma_m^2\tau_c$, demonstrating the immediate falsifiability of the framework.

3. Discussion

Within the present framework, wave–particle duality is treated operationally rather than interpretationally. The model identifies a dynamical mechanism—stochastic kinetic-phase modulation arising from mass–energy fluctuations—that reproduces wave-like interference during propagation while remaining fully compatible with localized detection events described by standard quantum mechanics. In this sense, the formal wavefunction dynamics are preserved, while the proposed mechanism supplies a physical process underlying the observed interference behavior without modifying measurement theory or the axioms of quantum mechanics.

Quantum uncertainty reflects unresolved mass-energy phase dynamics rather than irreducible indeterminacy.

The framework is compatible with quantum mechanics, quantum field theory, and relativistic energy equivalence, and it naturally connects interference, decoherence, and uncertainty within a single dynamical picture.

4. Conclusion

I have shown that the double-slit experiment admits a concrete physical explanation when particle mass is treated as a dynamically fluctuating quantity undergoing spontaneous mass-energy interconversion. Interference arises from coherent stochastic kinetic phases, while particle-like localization emerges naturally at detection. The theory yields testable predictions, admits experimental bounds, and offers a physically grounded origin for wave-particle duality without altering the formal structure of quantum mechanics.

5. Methods

5.1 Stochastic modeling

Mass fluctuations were modeled as a stationary Gaussian process with zero mean and exponential correlation function. Ensemble averages were evaluated using standard cumulant expansion techniques.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT in order to improve literacy and formatting. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

5.2 Visibility derivation

Fringe visibility was obtained by evaluating the ensemble-averaged interference term under Gaussian phase noise, yielding exponential decay in the long-time limit.

5.3 Path-integral formulation

The fluctuating mass was incorporated into the classical action, and interference suppression was obtained by averaging over stochastic action differences between paths.

5.4 Data availability

No new experimental data were generated. All constraints discussed are derived from published interferometry experiments.

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